

Topographic Influence on Internal Waves and Mesoscale Oceanic Dynamics, Including Lateral and Vertical Mixing in Marginal Zones of North Atlantic

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LONG TERM GOAL

The long-term goal of our research is to identify and quantify key processes responsible for vertical and lateral mixing in oceans, which influences transports of heat, energy, momentum, dissolved matter and plankton in pelagic and littoral oceans.

OBJECTIVES

The main objective of the project is to conduct a comprehensive analysis of small and mesoscale phenomena, focusing on oceanic marginal zones. Mixing, internal waves and transformation of water masses were of major concern during the last year. We continued the development of a web-accessible database containing mooring and profiling measurements taken by Russian oceanographers in deep basins of the Atlantic, Pacific, and Indian oceans, at trans-Atlantic sections and in the marginal seas of western Pacific. Collection of new data pertinent to turbulent mixing in the near-surface boundary layers, both from oceanic and atmospheric sides, was an important part of our work.

APPROACH

We analyzed existing measurements on internal waves influenced by topography in deep ocean and near shelf breaks in conjunction with results from numerical simulations, studied the nature of fine structure in various waters of the equatorial Atlantic, and conducted new measurements of turbulence, thermohaline structure and currents in the North Atlantic in collaboration with Russian, Spanish, and Canadian scientists onboard of r/v Akademik Ioffe (Russian Academy of Sciences). This research cruises allowed obtaining of new CTD and ADCP measurements (Drs. E. Morozov and S. Shapovalov, P.P. Shirshov Institute of Oceanology, RAS) at trans-Atlantic sections along 53°N. Concurrent measurements of the upper-layer oceanic turbulence (Dr. E. Roget, University of Girona, Catalonia, Spain) and atmospheric turbulence (Dr. K. Kreyman, MacMaster University, Canada) were also made.

WORK COMPLETED

The oceanographic database on the EFDP web site was extended to include new measurements taken in cooperation with oceanographers of the P.P. Shirshov Institute of Oceanology, RAS. The later include CTD data obtained in 1999 (*Shapovalov et al.* 2000) and 2000 (*Sokov et al.* 2001a) at two

trans-Atlantic sections along 48°N and 7°N. The data can be accessed via clicking maps on the EFDP website <http://www.eas.asu.edu/~pefdhome/Research/Ocean/oceanres.htm>. The data were preprocessed with a vertical resolution of 2 m. Descriptive analyses of main thermohaline features are also given in conjunction with each transect presented on the web.

The analysis of vertical mixing on the Black Sea shelf was completed; and a paper containing the results has been accepted for publication in JPO (*Lozovsky and Fernando* 2001). Our investigations of shelf dynamics using profiling and mooring measurements were continued, focusing on coastal zone of the Peter the Great Bay of the Japanese Sea. Of main interest were internal wave transformations and thermocline splitting near the shelf break. The results of this work have been presented at 2001 TOS conference in Miami (*Lozovsky et al.*, 2001c).

We completed analysis of the spatial decay of tidal internal-wave (TIW) energy generated at the Mascarene ridge in Indian Ocean and a chain of seamounts Heyres-Irving-Cruiser in the eastern Atlantic. The results of this study have been submitted for publication in JGR (*Lozovsky et al.* 2001b). Data from both regions showed almost identical rate of spatial decay of baroclinic tidal energy, which could be approximated by a power law close to an inverse dependence with distance from the topography. The energy density of baroclinic semidiurnal tide becomes insignificant compared to the background GM level at distances of about 2000 km from the Mascarene ridge.

An investigation on the propagation of Antarctic bottom water toward equator was conducted using CTD measurements taken in 2001 in the Equatorial Atlantic as well as historical data sets. It has been suggested (*Lappo et al.* 2001) that the significant decrease of the near-bottom temperature observed northward the equator in 2001 may be related to the decline of atmospheric temperature in the southern hemisphere observed in early 1940s.

A new cruise in the North Atlantic was completed in April-May, 2001 with one of the PIs (I. Lozovsky) onboard of r/v Akadimik Ioffe. Forty-two CTD stations located between Canadian shelf and coastal zones of Ireland were taken along 53°N from the sea surface to the very bottom. These data were accompanied by ADCP measurements in the upper 600 meters. More than 90 casts were made using a free-falling microstructure profiler. In the atmospheric side, continuous measurements of turbulence were made by a sonic anemometer, with most measurements belonging to stormy weather conditions. These data will be used for investigations of air-sea interactions under high winds and high-amplitude surface waves as well as for studying fine structure and turbulence in drift currents and frontal marginal zones.

RESULTS

A. Thermocline splitting and internal waves on the shelf break of Japanese Sea

We analyzed towing, profiling and mooring measurements taken over several years by Dr. Navrotsky in the coastal zone of the Peter the Great Bay of the Japanese Sea. The deepening and splitting of the thermohalocline were identified at several across-shelf sections (Fig. 1). Deformations of the thermocline that can be associated with a hydraulic jump originating at the continental slope at distances 5-15 miles from the shelf break could be identified. A narrow horizontal seasonal thermocline that occupies a depth range between 20 and 40 m in the open sea dipped down by 20-30 m as the shelf break is approached. At times this sharp thermocline thickened over the shelf break,

followed by splitting into two new interfaces. Further splitting of sub-layers between the two interfaces occurred several miles shoreward from the shelf break. Internal-wave-induced mixing within the thermocline appears to be a possible mechanism for the generation of a multi-layered thermocline in the coastal zone.

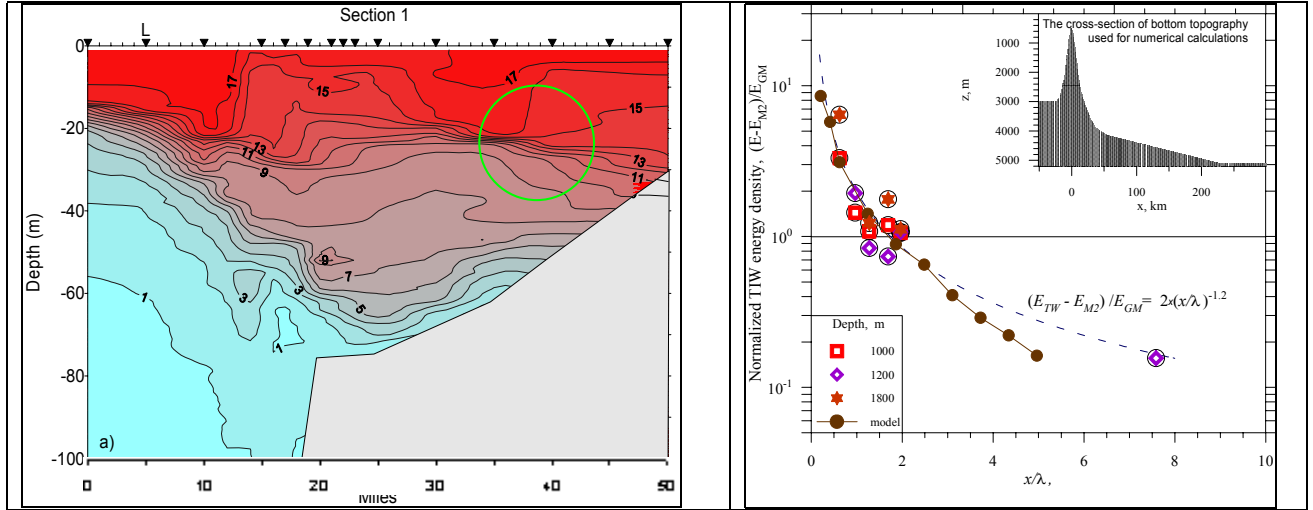


Fig. 1 (left panel). Temperature contour plots over the slope and shelf break at zonal transect along 132° E. Secondary splitting of the narrow thermocline is marked by a circle.

Fig 2 (right panel). A comparison between numerical model calculations of the TIW energy density normalized by the GM energy E_{GM} at $z = 1200$ m (solid dots) and the observations east of Mascarene ridge at $z = 1000 - 1800$ m. The energy of the barotropic constituent M2 was subtracted from the total energy of semidiurnal oscillations obtained from mooring records. The geometry of the bottom relief used for calculations is in the inset.

B. Spatial decay of tidal internal waves

Preliminary results on the investigation of spatial decay of TIW energy density generated near the Mascarene ridge in Indian Ocean were presented in our F00ONR annual report; also see *Lozovsky et al.* (2000a). This work was extended to include field data from the Canary Basin of eastern Atlantic and numerical simulations of relevant flows. We estimated the energy density associated with internal tides E_{TW} vis-à-vis the energy of the background internal wave field E_{GM} given by the Garrett-Munk model. The spatial decay of TIW could be approximated by a power law close to that shown in Fig. 2, which fits the composite set of mooring data reasonably well. The energy density of the first mode of internal tides becomes negligible compared to the background internal wave field (less than 10% of the GM level) beyond about 2000 km from the ridge, which is about 10-12 wavelengths of the first mode.

An advance version of the numerical model proposed by *Morozov and Vlasenko* (1966) was used to calculate the TIW energy density at various distances from the topography. The results, normalized by E_{GM} are shown in Fig. 2, (solid dots) along with field data from the depth range 1000 – 1800 m. The

model calculations accord reasonably well with observational samples for $x/\lambda < 5$. The model results (Fig. 2) also suggest a power law dependence with least squared power fit indicated by the dashed line having a coefficient of determination $r^2 = 0.83$. The agreement between observations and numerical calculations gives further credence for the estimates of spatial energy decay based on inverse power functions. Numerical calculations, however, shows more rapid decay of TIW energy density for $x/\lambda > 5$ than deduced from the observations. At a considerable distances from the topography, model calculations predict less tidal energy than observed, indicating the possibility of additional sources of internal tide generation that were not included in the model.

C. Fine structure of major water masses in the equatorial Atlantic

Using CTD profiling data obtained in the equatorial Atlantic in the year 2000, we identified predominant thermohaline fine structure associated with various water masses of different origins.

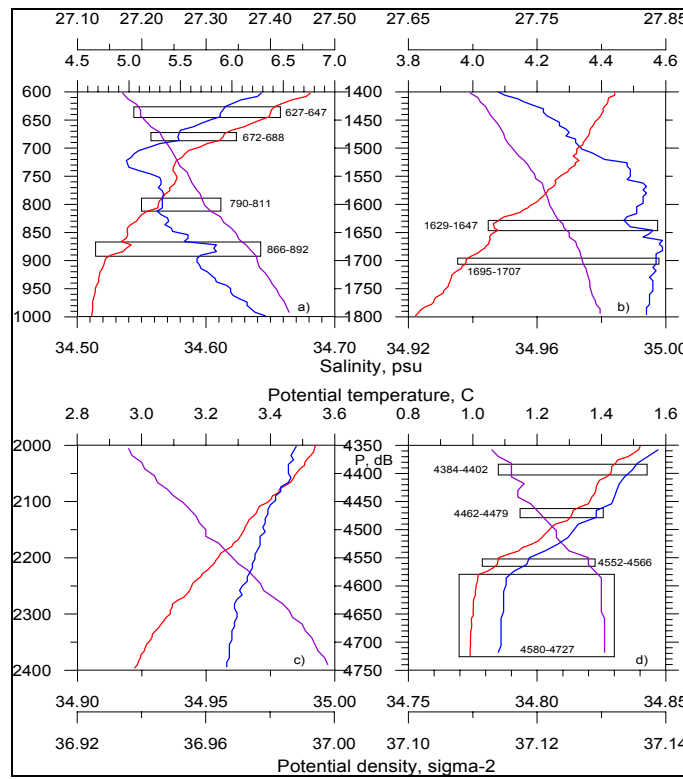


Fig. 3. Typical fine structures associated with major waters of the equatorial Atlantic: intrusive - AAIW (a) and upper NADW (b), weak internal wave induced irregularities – mid-NADW (c), and step-like structure of turbulent origin - AABW (d).

Below the upper 500-meter layer, the following major water masses were identified (Sokov *et al.* 2001b): Antarctic Intermediate Water (AAIW, $600 < z < 1400$ m), North Atlantic Deep Water (NADW, $1400 < z < 3700$ m) and Antarctic Bottom Water (AABW, $z > 4100$ m). The bottom and upper boundary layers at this transect contained mostly step-like fine structure whereas the intermediate waters were full of intrusions. Examples of potential temperature, density, and salinity profiles for the main water masses are shown in Fig. 3. Waters of the Antarctic origin (Fig. 3 a,d) are

richer in fine structure compared to North Atlantic waters (Fig. 3b,c). There are only weak fine structure details in Fig. 3c that are most likely caused by internal waves in mid-NADW. A few quasi-homogeneous layers and temperature inversions with a thickness of 10-20 m can be identified in Fig. 3b. These elements of the upper NADW are associated with a salinity maximum of Mediterranean origin. Stable salinity stratification prevents double-diffusive convection here. On the contrary, estimates of stability parameter R_ρ showed that salt-fingering is a possible mechanism of step-like structure formation in the upper AAIW (Fig. 3a). In the lower AAIW ($z > 800$ m), intrusive fine structure is most likely formed due to isopycnal advection because inversions in temperature and salinity compensate each other in density profiles. Intrusions in AAIW are tied to the maximum of silicate concentration, indicating a boundary between AAIW and the Upper water of the Circumpolar Current. It is likely that the generation of fine structure at this boundary increases the rate of exchange of thermohaline properties, thus further reducing disparities in T,S characteristics.

The Antarctic bottom water contains predominantly step-like fine structure (Fig. 3d). Several steps with thickness from 14 to 18 m can be seen above approximately homogeneous 150-meter near bottom boundary layer. These layers cannot be of salt-finger origin given the high mean density ratio ($R_\rho = 5$) there. The bottom water flows toward the equator along relatively narrow channels. Mixing due to bottom and lateral boundary roughness explains why a thick homogeneous layer appears near the bottom and how quasi-homogeneous steps can be formed in the overlaying pycnocline due to boundary mixing. A numerical model was developed to describe the generation of such step-like structure (Lozovatsky *et al.* 2000b). The formation of prominent fine structure in the bottom boundary layer enhances the changes of water properties of AABW when it moves north, in contrast to slow transformation of the overlying NADW moving south.

IMPACT/APPLICATION

Historical data sets collected by Russian oceanographers during the 1980's and new data taken in 1999-2000 are now available to the international oceanographic community via Internet. These data can be used to acquire better understanding on internal-wave dynamics, thermohaline fine structure, and mesoscale and large-scale flows.

TRANSITIONS

The new datasets were posted on <http://www.eas.asu.edu/~pefdhome/Research/Ocean/oceanres.htm>. The database is frequently upgraded by adding new information and convenient features for general use.

RELATED PROJECTS

The Co-P.I. is involved in two other ONR funded projects dealing with laboratory investigations of waves in coastal zone, their breaking and interacting with solid objects. These projects are funded by Marine Geophysics and Coastal Dynamics Programs of ONR.

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